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ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND ABERD--ETC F/8 19/6  
A TWO-DIMENSIONAL, TWO-PHASE FLOW SIMULATION OF IGNITION, FLAME--ETC(U)  
JUL 82 A W HORST, F W ROBBINS, P S GOUGH  
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TECHNICAL REPORT ARBRL-TR-02114

A TWO-DIMENSIONAL, TWO-PHASE FLOW  
SIMULATION OF IGNITION, FLAMESPREAD,  
AND PRESSURE-WAVE PHENOMENA IN THE  
155-MM HOWITZER

A. W. Horst  
F. W. Robbins  
P. S. Gough

July 1962

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND  
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AMBEREN PROving Ground, Maryland

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report ARBRL-TR-02414	2. GOVT ACCESSION NO. AD A119 148	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Two-Dimensional, Two-Phase Flow Simulation of Ignition, Flamespread, and Pressure-Wave Phenomena in the 155-mm Howitzer	5. TYPE OF REPORT & PERIOD COVERED October 1980-September 1981	
7. AUTHOR(s) A.W. Horst, F.W. Robbins, P.S. Gough*	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: DRDAR-BLI Aberdeen Proving Ground, MD 21005	8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command US Army Ballistic Research Laboratory (DRDAR-BL) Aberdeen Proving Ground, MD. 21005	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L161102AH43	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12. REPORT DATE July 1982	
	13. NUMBER OF PAGES 33	
	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES *Paul Gough Associates Inc. Portsmouth, NH		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Interior Ballistics      Computer Codes Guns                      TDNOVA Flamespread Pressure Waves		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Past attempts to simulate two-phase flow phenomena in high-performance, bagged-charge artillery using available one-dimensional, two-phase flow interior ballistic codes have met with only limited success, presumably because of the inability of these models to capture configurational complexities associated with the charge/chamber interface. Previous work with a quasi-two-dimensional version of one such code (NOVA), in which the charge and unoccupied regions in the gun chamber were treated as disjoint but coupled regions of one-dimensional		

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flow, revealed that early flow external to the charge can alter the flame path and equilibrate pressures throughout the gun chamber. Moreover, characteristics of the bag material itself - strength and permeability, affecting both communication of gases between the charge and external regions and persistence of circumferential ullage - can have significant impact on the development of longitudinal pressure waves in the tube.

Yet these calculations recognized only an axial thermal stimulus in the propellant bed and ignored entirely the structure of the radial flow field in the two-phase medium. Current work addresses application of a fully two-dimensional, axisymmetric, two-phase flow model (TDNOVA) to the bagged-charge problem, providing for the first time an explicit treatment of two-dimensional flamespread in this configurally complex environment. Functioning of the basepad/centercore igniter is included within the physical scope of the model, as is the presence of reactive parasitic charge components which exhibit exothermic or endothermic properties in addition to resistance to gas and solid-phase flows.

Results are presented for the 155-mm, M198 Howitzer, firing the top-zone M203 Propelling Charge, with code input varied to reflect changes in the above-mentioned parasitic-component characteristics and in charge/chamber interface. Comparison is made with previously published calculations as well as with experimental data.

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## I. BACKGROUND

Theoretical and experimental efforts continue to bring about an improved understanding of the detailed phenomenology of the gun interior ballistic cycle. Investigators addressing ignition and combustion processes<sup>1-3</sup> have been joined by those interested in the details of heat transfer to and erosion of the bore surface<sup>4,5</sup>. Our work has focused on the process of flamespreading as a hydrodynamic problem and on the influence of the path of flamespreading on the longitudinal pressure field throughout the entire interior ballistic cycle. In this study, we further limit our attention to bagged propelling charges, the configurational complexities of which are particularly challenging to modeler and designer alike.

In a previous paper<sup>6</sup>, we presented simulations of a bagged charge based on two modeling representations: first, a one-dimensional-with-area-change treatment which assumed a uniform cross-sectional distribution of propellant within the chamber at any given axial location; and second, a quasi-two-dimensional analysis which treated the propelling charge and unoccupied regions in the gun chamber as disjoint but coupled regions of one-dimensional flow. The latter description also allowed some recognition of the permeability and strength of the bag sidewall to be embedded in the representation as boundary conditions linking the coaxial regions of one-dimensional flow.

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<sup>1</sup>E.B. Fisher, "Continued Development and Documentation of the Calspan Interior Ballistics Code," Calspan Report No. 6689-D-1, Calspan Corporation, Buffalo, NY, February 1981.

<sup>2</sup>P.S. Gough, "The Flow of a Compressible Gas Through an Aggregate of Mobile Reacting Particles," IHCR 80-7, Naval Ordnance Station, Indian Head, MD, December 1980.

<sup>3</sup>K.K. Kuo and J.H. Koo, "Transient Combustion in Granular Propellant Beds. Part 1: Theoretical Modeling and Numerical Solution of Transient Combustion Processes in Mobile Granular Propellant Beds," BRL-CR-346, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1977 (AD #A044998).

<sup>4</sup>H.J. Gibeling, R.C. Buggeln, and H. McDonald, "Development of a Two-Dimensional Implicit Interior Ballistic Code," ARBRL-CR-00411, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1980. (AD A084092)

<sup>5</sup>A.C. Buckingham, "Research on Gun Barrel Erosion Mechanisms," Energy and Technology Review, Lawrence Livermore Laboratory, CA, January 1979.

<sup>6</sup>A.W. Horst and P.S. Gough, "Modeling Ignition and Flamespread Phenomena in Bagged Artillery Charges," ARBRL-TR-02283, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1980. (AD A091790)



Calculations using the quasi-two-dimensional model revealed the path of flamespread to be sensitive to both bag configuration and material characteristics, with a persistence of circumferential ullage external to the bag providing a path for equilibration of the longitudinal pressure field. The influence of this path was greatly diminished, however, when axial ullage was not present at the downstream end of the chamber; in this case, predictions were essentially equivalent to those provided by the simpler, one-dimensional representation. The influence of radial flow, including flame propagation, within the two-phase medium itself could not, of course, be assessed with either of these models. We report herein on calculations performed using a fully two-dimensional, axisymmetric, two-phase flow model to describe igniter functioning, flamespread, and pressurization in a 155-mm howitzer.

## II. TECHNICAL DISCUSSION

### A. Description of the Problem

The 155-mm, M203 Propelling Charge is a conventional, top-zone, bagged charge currently employed with the 155-mm, M198 Towed Howitzer. Depicted in Figure 1, this charge employs about 11.8 kg of M30A1, triple-base, granular propellant. The ignition system is composed of a cloth basepad containing 28 g of Class 1 black powder and a molded-nitrocellulose centercore tube, which houses a cloth snake filled with an additional 113 g of black powder. The charge, confined within a resin-impregnated cloth bag, is encumbered with a number of parasitic components, each designed to perform a special function. A cloth donut filled with granular potassium sulfate serves to reduce muzzle flash. Lead foil, a de-coppering agent, and a titanium dioxide/wax wear-reducing additive are also present as liners which surround approximately the forward two-thirds of the charge. Finally, a cloth lacing jacket provides additional rigidity to the package.

The normal sequence of events during functioning of this charge begins when hot combustion products from the primer exit the spithole in the spindle face and impinge upon the basepad. As the basepad begins to burn, product gases and hot particles penetrate the several layers of cloth, enter the centercore tube, and ignite the snake as intended. However, basepad combustion products may also penetrate the rear of the bag and ignite the main propellant charge directly. This competition with centercore functioning is critical, and a victory for direct, local ignition of the propellant bed by the basepad could lead to catastrophic pressure waves in a high-loading-density charge. Basepad and other early combustion products can also flow into the axial ullage behind the charge, through the circumferential ullage around the bag, and into the axial ullage in front of the bag as shown in Figure 2. Such flow around the bag can equilibrate pressures throughout the chamber early in the cycle, but the persistence of this ullage is unknown and may depend heavily on charge-component characteristics. Further, a possible variation in charge standoff from the spindle face can be expected to affect coupling between primer spithole output and the basepad, as well as alter the initial distribution of propellant and ullage.

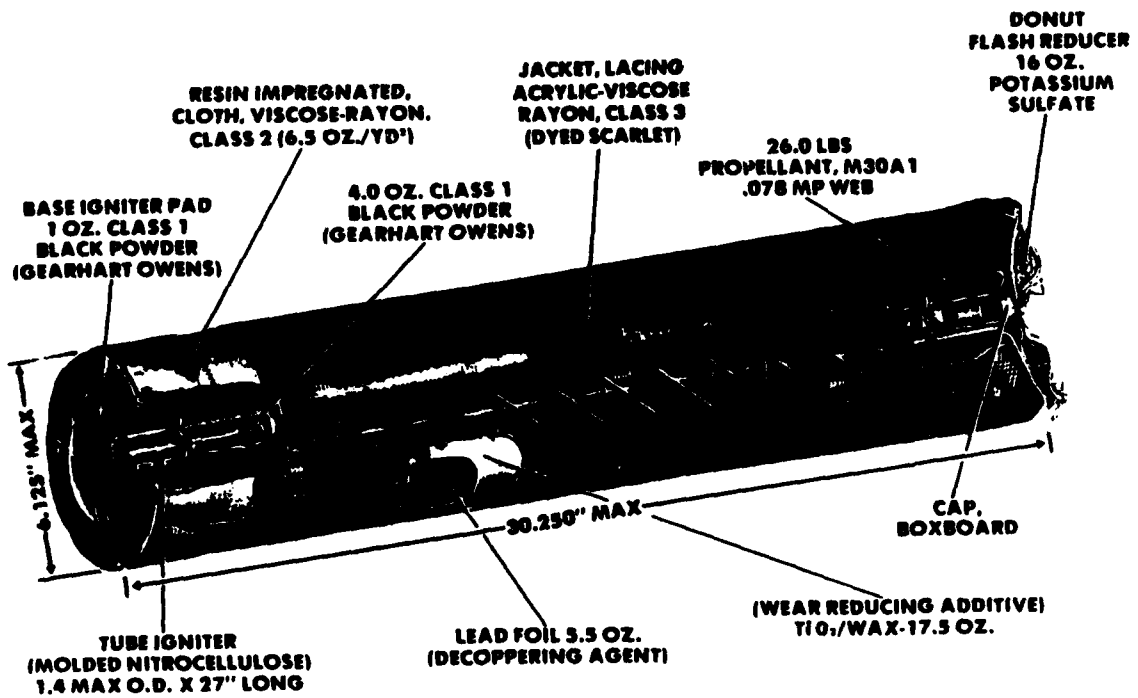


Figure 1. 155-mm, M203 Propelling Charge

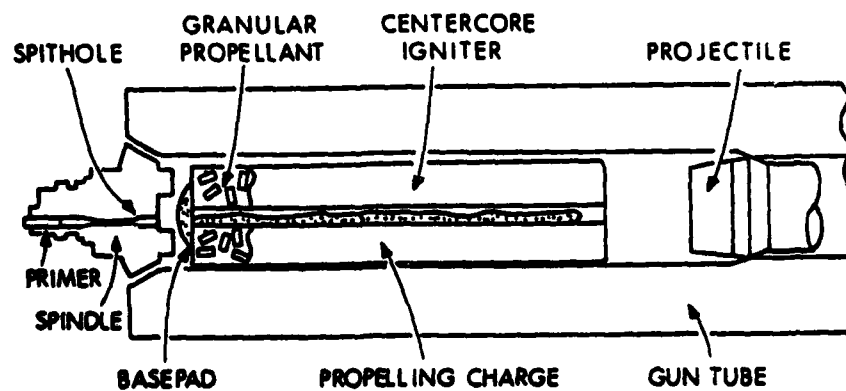


Figure 2. Bagged Charge/Gun Chamber Interface

## B. Modeling Approach

Simulations presented in this paper were performed using TDNOVA<sup>7</sup>, an unsteady, two-dimensional, axisymmetric, two-phase flow representation of the interior ballistic cycle. The development of TDNOVA was undertaken largely in response to the configurational complexities of bagged charges which fell outside the physical scope of the previously-developed, one-dimensional NOVA code<sup>8</sup>.

Flamespread through bag charges is believed to be influenced strongly by details of the ullage which initially surrounds the bag and by the behavior of the bag material itself. Accordingly, an explicit representation is made in TDNOVA of the region occupied by the propelling charge at any time. The flow in the ullage, which surrounds the region occupied by the propellant, is represented as unsteady, inviscid, and single phase.

The ullage is divided into several disjoint regions, coupled to one another and to the two-phase flow in the propelling charge by means of finite jump conditions at all their mutual boundaries. By formulating the theory in such a manner as to use directly the jump conditions at the boundary of the bag, we provide a direct mechanism for the representation of the influence of the bag. Impermeability is reflected directly within the momentum jump condition as a quasi-steady flow loss. Similarly, the influence of exothermically reactive components, such as the basepad and centercore tube, and endothermically reactive components, such as the salt bag, are reflected by means of source terms in the mass and energy jump conditions.

The division of the ullage into several regions is based on the instantaneous configuration of the external boundaries, namely the breech, the tube, and the moving projectile, and on the configuration of the bag which predicates regions of ullage behind it, ahead of it, around it, and within it. Each such region of ullage is treated as lumped parameter, quasi-one-dimensional, or as fully two-dimensional, in accordance with criteria based on its dimensions.

In addition to the representation of a basepad and centercore tube within the structure of the bag, the model recognizes the influence of a centercore ignition charge, coaxial with the bag and moving with it, and which is represented as a quasi-one-dimensional, two-phase flow. As with the ullage, the centercore is coupled to the state of the flow within the bag and, where applicable, the ullage at the ends of the chamber, by reference to finite jump conditions. The representation of the ignition

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<sup>7</sup>P.S. Gough, "A Two-Dimensional Model of the Interior Ballistics of Bagged Artillery Charges," ARBRL-CR-00452, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1981. (AD A100751)

<sup>8</sup>P.S. Gough, "The NOVA Code: A User's Manual. Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, December 1980.

train also admits the specification of an externally injected stimulus of predetermined flow rate and energy.

Each region of continuous flow properties is mapped onto a regular geometric figure, a line or a square, by means of a boundary-fitted-mesh-transformation algorithm. The method of solution is based on an explicit, two-step marching scheme which utilizes the characteristic forms of the balance equations at the external and the internal boundaries.

Figure 3 depicts schematically the level of representation provided by TDNOVA, along with the one-dimensional-with-area-change and quasi-two-dimensional approximations employed in our previous discussion<sup>6</sup>.

### C. Calculations

Those features of the input data base not associated with the multidimensionality of the problem have been reported previously<sup>6</sup>. A schematic representation of additional, configurational information required by TDNOVA is provided as Figure 4. We observe that the assumption of axisymmetry leads to an annular distribution of ullage external to the bag sidewall.

Initially, a fully two-dimensional analysis of flow within the two-phase medium is provided. In the calculations described, however, the regions of ullage contiguous to the bounding surfaces of the bag are treated as quasi-one-dimensional (i.e., one-dimensional-with-area-change), the continuum coordinate being defined by the boundary. Corner regions of ullage are given a lumped-parameter representation. The centercore ignition charge is treated as a one-dimensional, two-phase flow, while the basepad is recognized in terms of an exothermic region of the rear boundary of the charge.

Following completion of flamespread, rupture of the bag sidewall, and equilibration of the radial structure of the pressure field to within some user-specified limit, a quasi-two-dimensional approach is introduced, similar to that reported previously<sup>6</sup>. For the duration of the interior ballistic cycle, the propelling charge is given a quasi-one-dimensional representation, as is the circumferential ullage, while regions of axial ullage at each end of the chamber are treated as lumped parameter.

It should be pointed out that a fully two-dimensional treatment of the ullage is available in TDNOVA. However, the two-dimensional nature of the flow in these regions may well be outside the scope of the inviscid gas flow equations currently used, and the quasi-one-dimensional description of flow in the ullage may be the better of the two options available.

We have provided quantitative estimates of the permeability and strength of various portions of the charge package; however, these values are based only on intuition or limited testing now underway at the Ballistic Research Laboratory. Further, it must be realized that no account is taken in the analysis of the independent motion of the bag, all packaging materials being treated as attributes of the surface of the propellant bed itself.

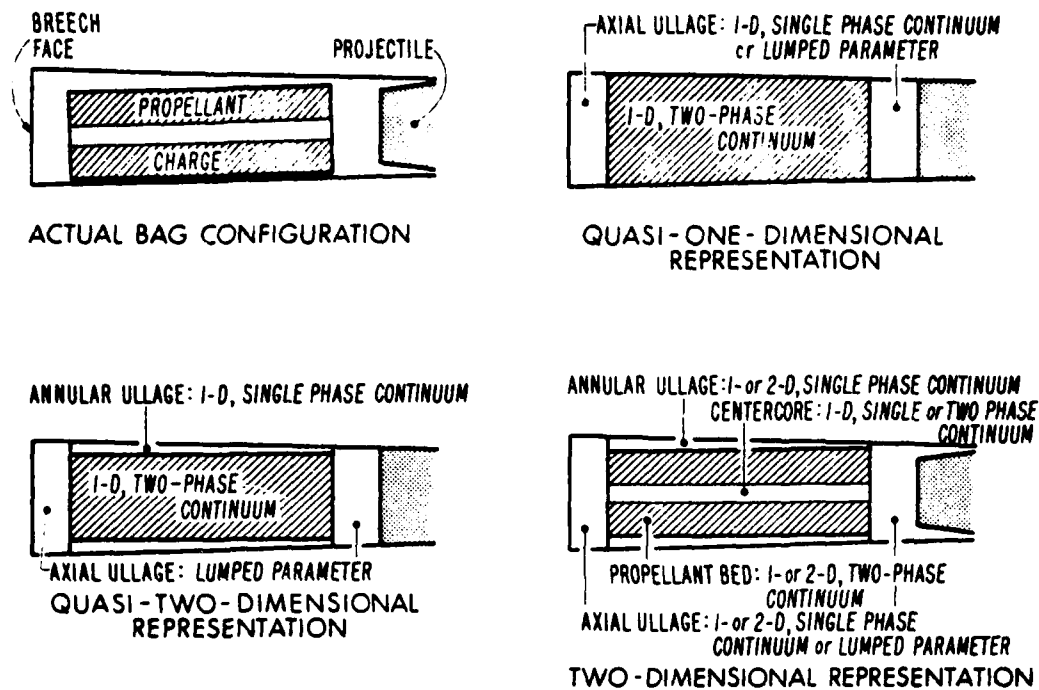


Figure 3. Schematic of Actual Interface and Model Representations

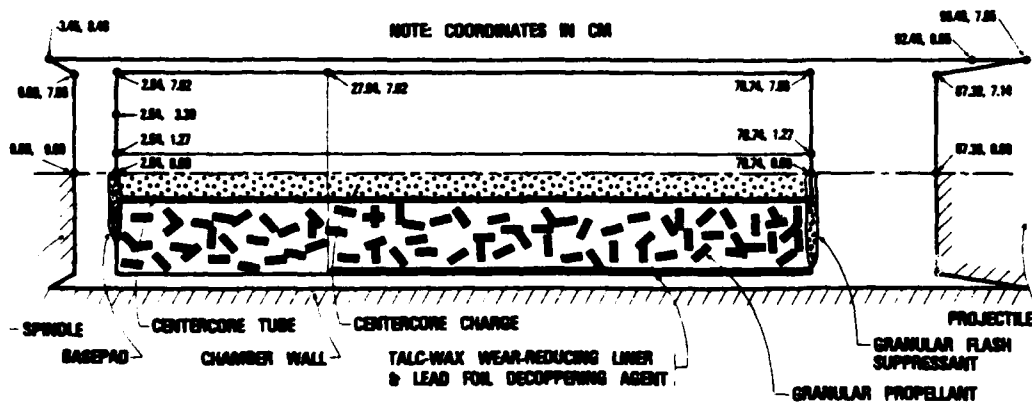


Figure 4. Two-Dimensional, Axisymmetric Representation of 155-mm, M203 Propelling Charge

Finally, we draw attention to the fact that an artificially-low ignition temperature (300 K) is provided for the black powder centercore to facilitate convectively-driven flamespread at low pressures, the discharge of hot molten salts being outside the current scope of the code. This compromise is consistent with our motive of treating the centercore igniter as a two-phase medium in order to capture the appropriate resistance to flow during the overall ignition event.

Turning now to the details of the solutions, we begin by addressing a calculation based on input data describing the 155-mm, M198 Howitzer firing the M203 Propelling Charge, positioned the nominal 25-mm from the spindle face. The initial thermal stimulus associated with functioning of a primer located in the breechblock lies outside the scope of the current representation and the calculation begins with combustion of the basepad. Figures 5 and 6 present isometric projections of the gas pressure and temperature fields at selected times during the early portion of the interior ballistic cycle. We note early pressurization and flamespread within the centercore, the centercore tube wall having been described as being initially impermeable to flow. However, a flow of hot combustion products external to the bag also takes place, which, because of the permeability of the rear portion of the bag sidewall, leads to early ( $t \approx 2$  ms) pressurization of the entire rear portion of the chamber. (The forward two-thirds of bag sidewall is given an initially-impermeable representation to reflect the presence of lead-foil and titanium dioxide/wax liners.) Indeed, a nearly one-dimensional pressure field results after only a few milliseconds. Nevertheless, flamespread, as depicted in Figure 7, clearly reflects the radial stimulus provided by the centercore igniter. Conversion to the quasi-two-dimensional representation rapidly follows the completion of flamespread, which occurs within 6 ms of the onset of basepad combustion for all calculations described. Resulting pressure-time and pressure-difference profiles are provided in Figure 8, along with previously-reported calculated results and experimental data. Also included in the figure is a recently-recorded, pressure-difference profile which is very closely approximated by the TDNOVA prediction. While providing an encouraging comparison between current theory and experiment, this difference from earlier experimental data highlights the problem of variability in pressure waves with bagged charges.

A companion calculation for the M203 Propelling Charge loaded at maximum standoff from the spindle face (i.e., pushed forward against the projectile base) yields the pressure-field plots presented in Figure 9. We note the presence of a strong, reverse pressure gradient (at  $\sim 3$  ms), often described in the past to be the consequence of a grossly one-dimensional flamespreading event resulting from improper functioning of the centercore. We note, however, that Figure 10 clearly depicts radial flamespread, suggesting the locally-high forward pressurization to be more the result of the initial distribution of propellant in the chamber than of anomalous behavior associated with vigorous, two-phase flow dynamics. Predicted pressure-time and pressure-difference profiles for this calculation are provided in Figure 11.

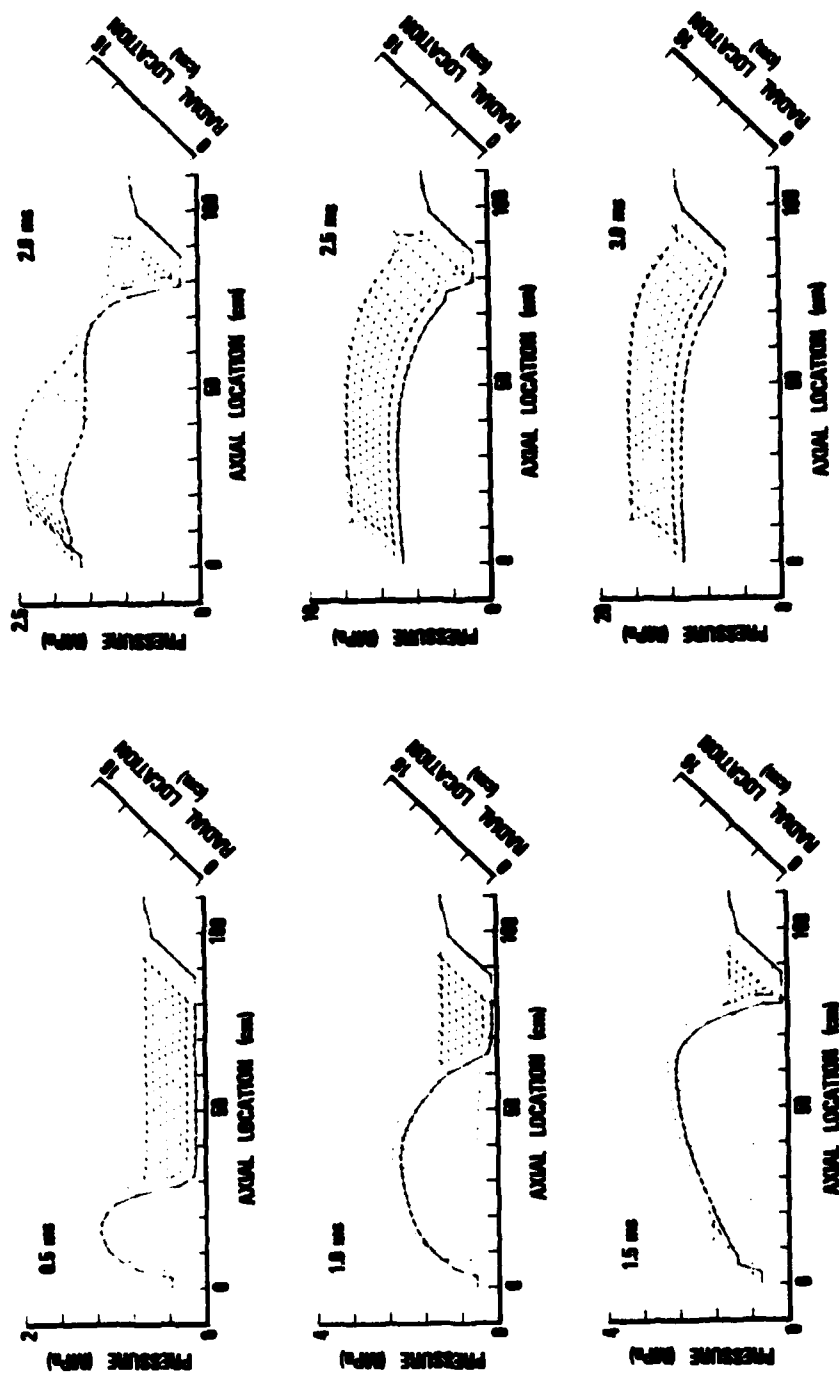


Figure 5. Predicted Pressure Field at Various Times for M203 Charge at 25-mm Standoff

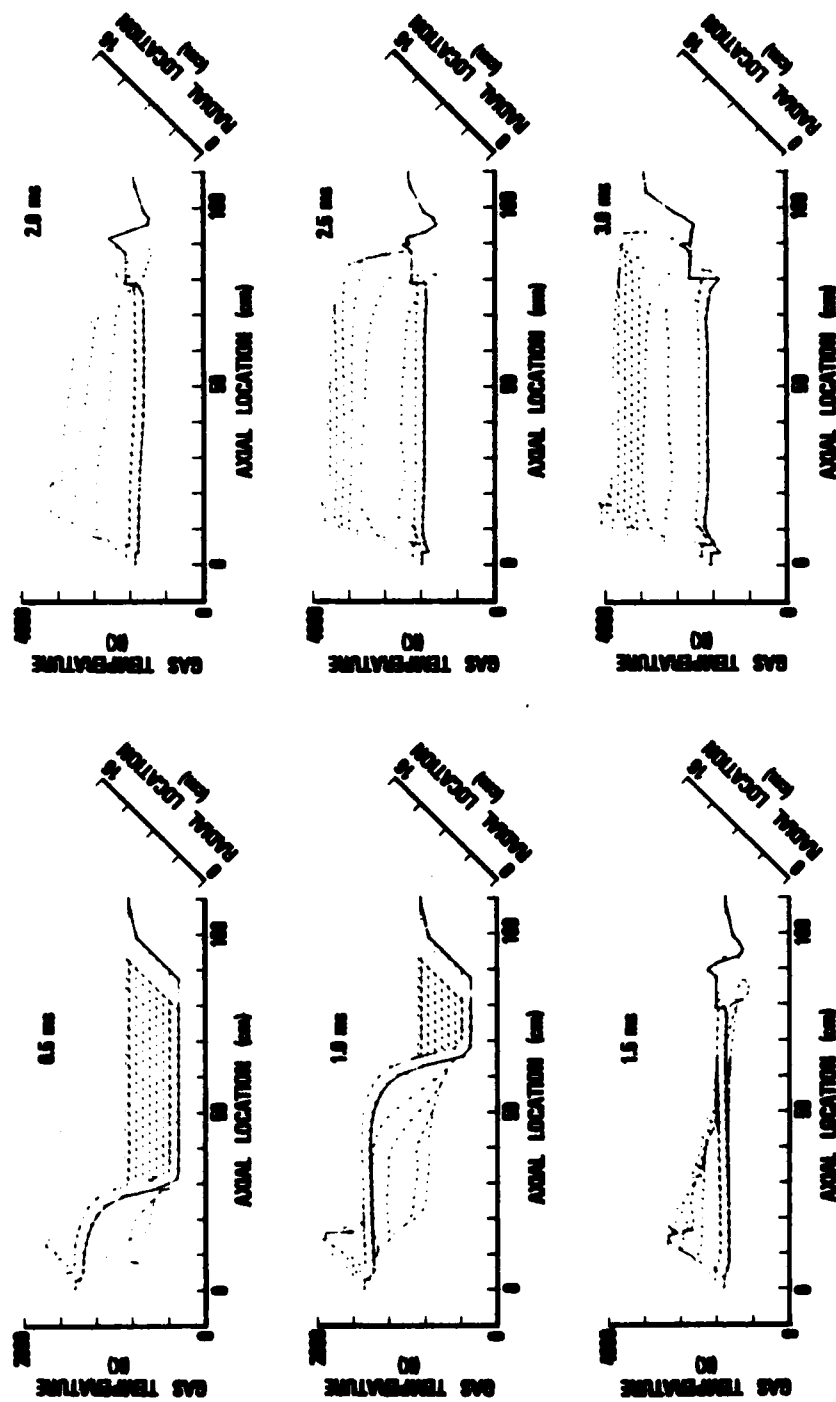


Figure 6. Predicted Gas Temperature Field at Various Times for M203 Charge at 25-mm Standoff



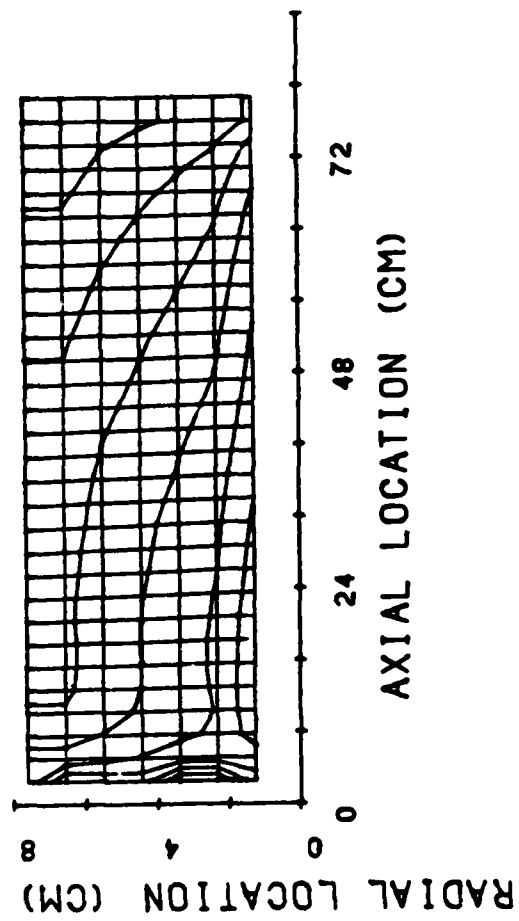


Figure 7. Predicted Flamespread Contours ( $\Delta t = 0.24\text{ms}$ ) for M203 Charge at 25-mm Standoff

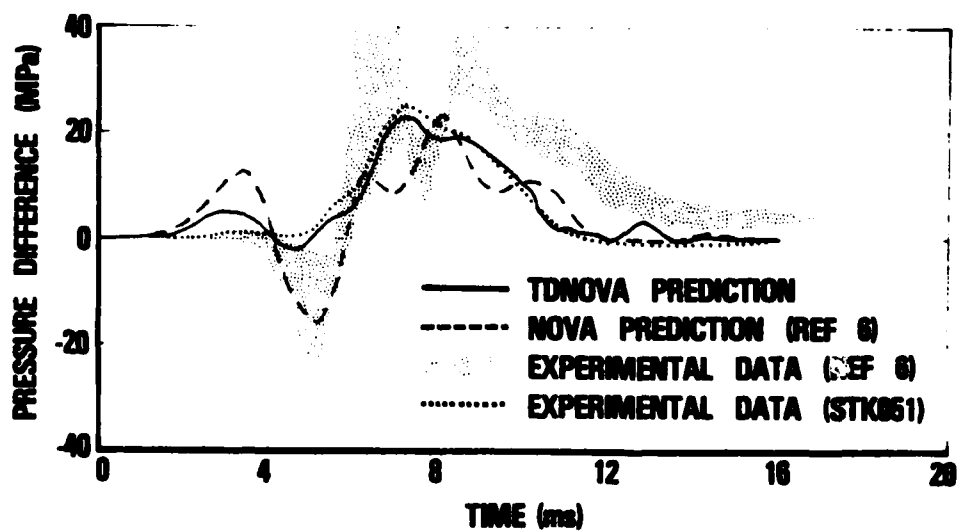
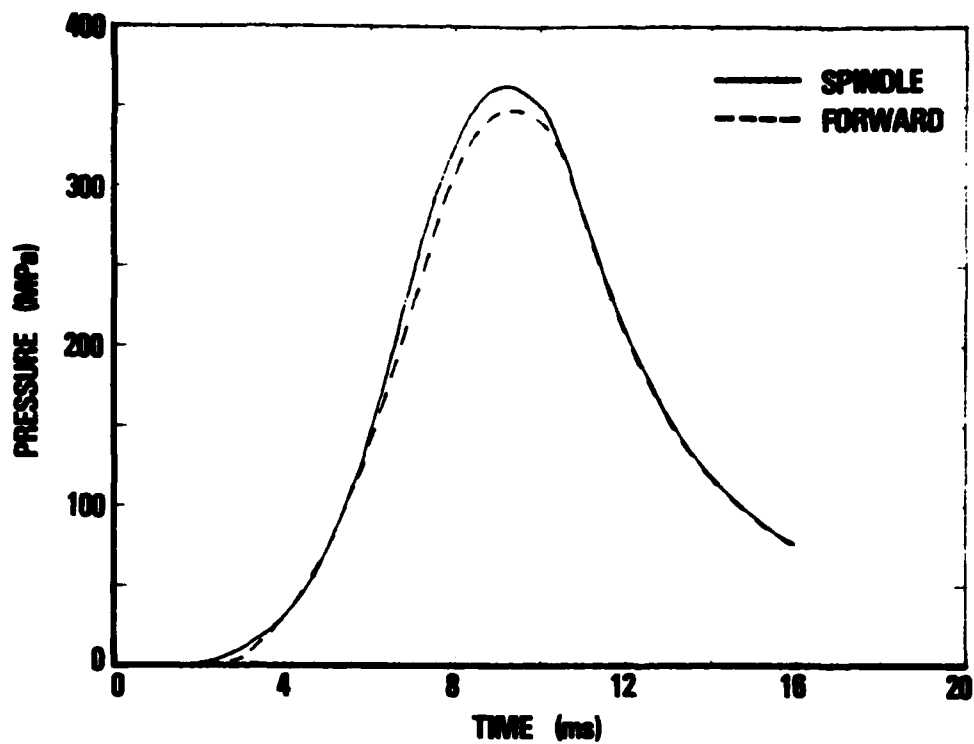


Figure 8. Pressure-Time and Pressure-Difference Profiles, Predicted and Experimental, for M203 Charge at 25-mm Standoff

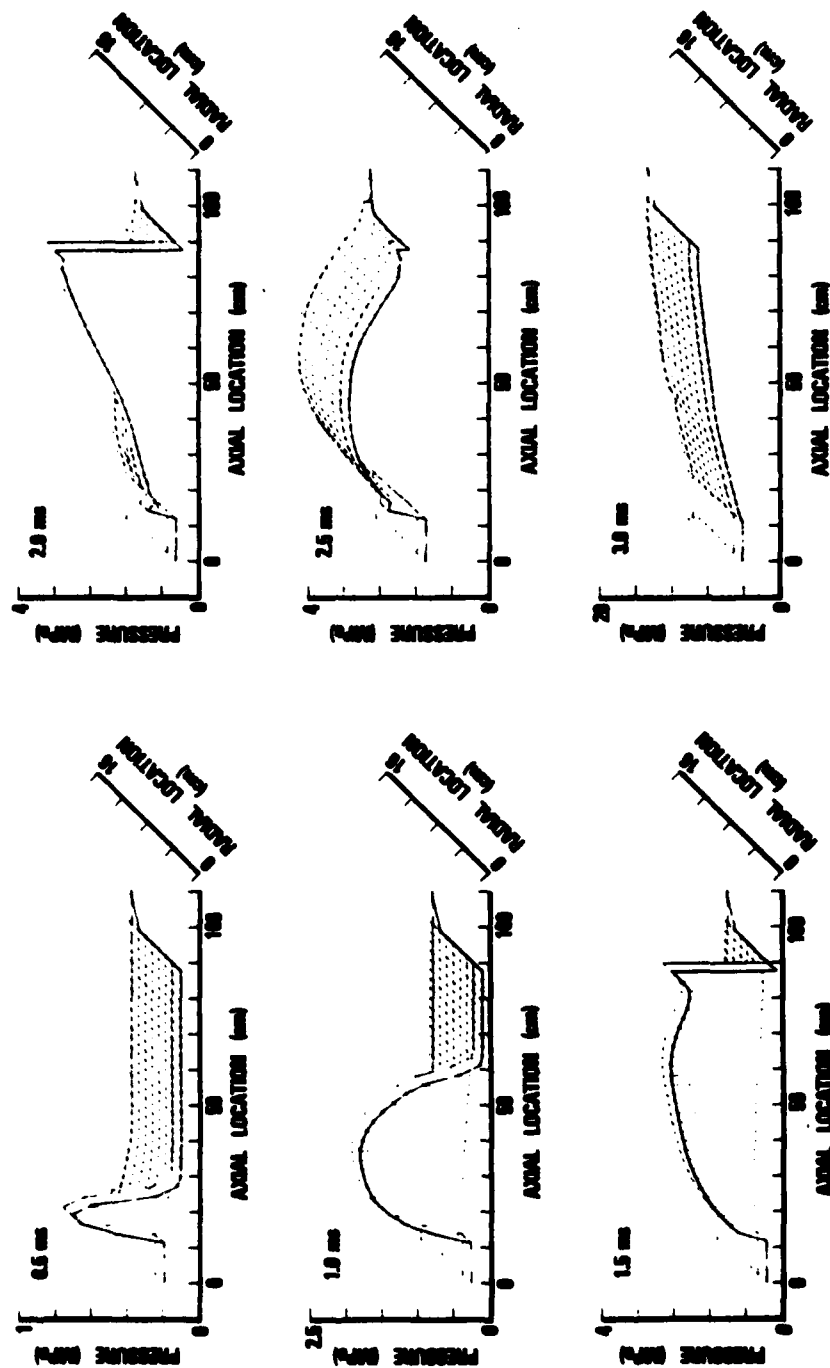


Figure 9. Predicted Pressure Field at Various Times for M203 Charge at Maximum Standoff

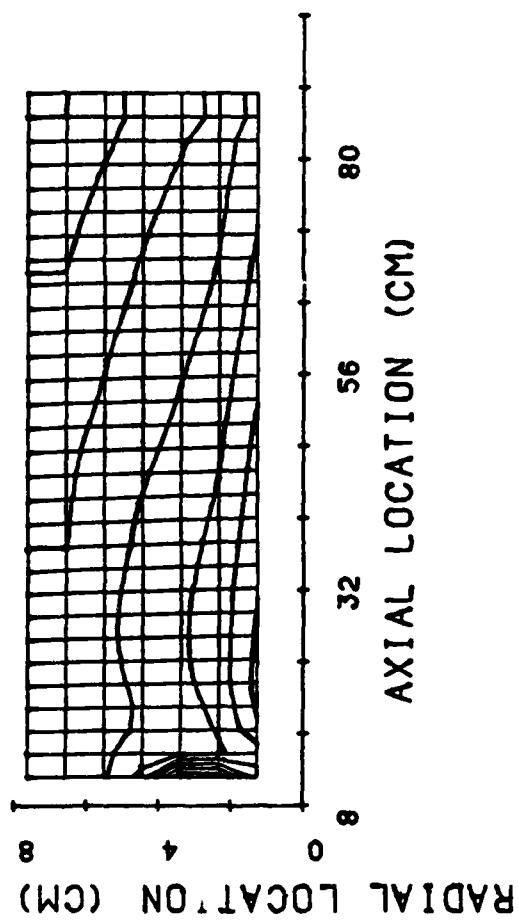


Figure 10. Predicted Flamespread Contours ( $\Delta t = 0.24\text{ms}$ ) for M203 Charge at Maximum Standoff

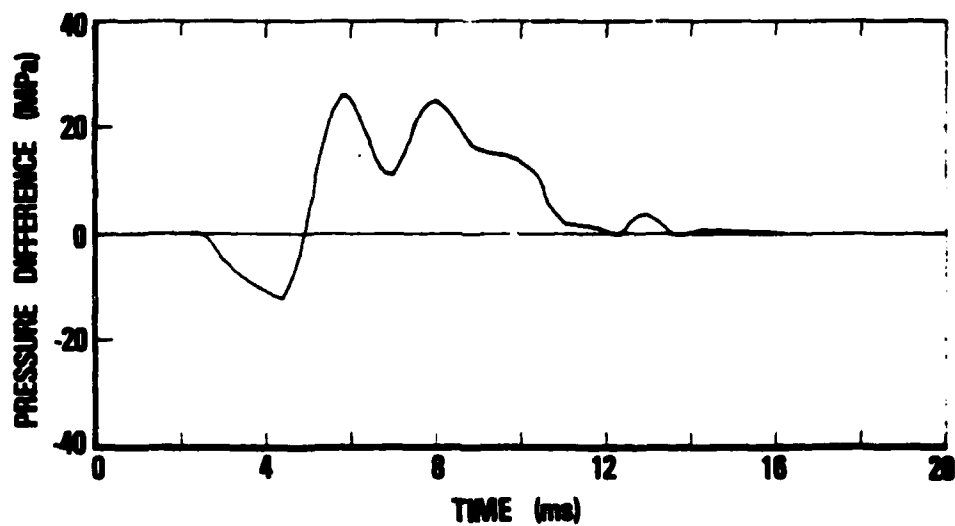
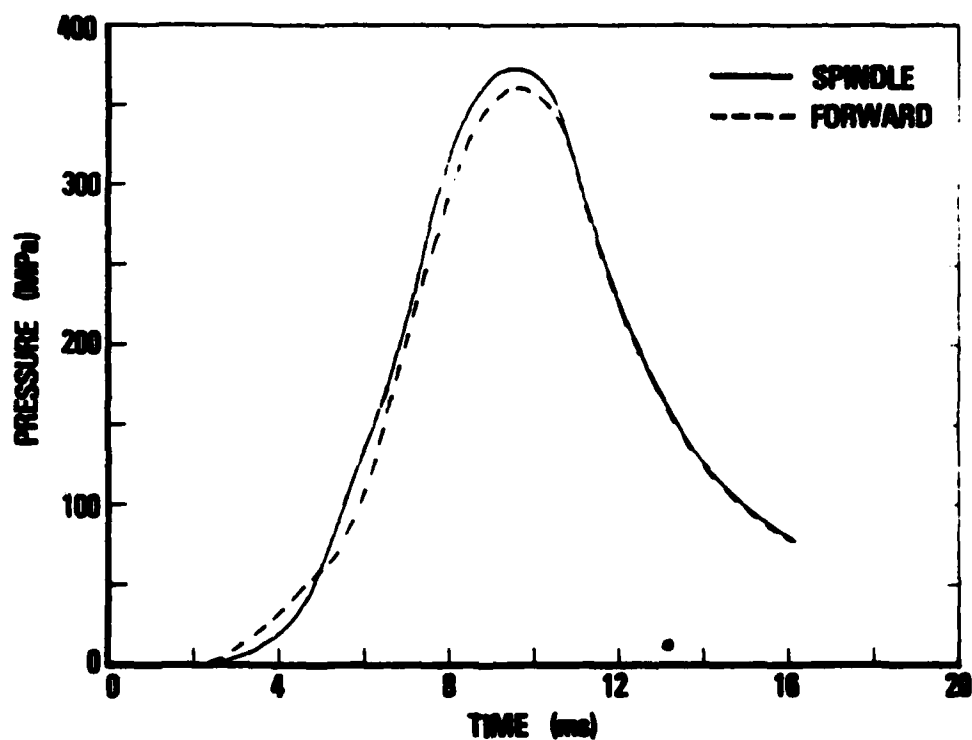


Figure 11. Predicted Pressure-Time and Pressure-Difference Profiles for M203 Charge at Maximum Standoff

Additional calculations were performed with TDNOVA using data bases altered to reflect the possible, early rupture of the bag sidewall and/or failure of the centercore igniter. Results from several of these calculations are displayed in Figures 12 and 13. Significant impact is observed, though the weak-bag condition (i.e., zero strength) did not lead to large pressure waves unless centercore functioning was delayed by at least a millisecond as well. This result suggests that localized ignition in addition to an unconfined propellant bed is required in order to effect the collapse of circumferential ullage against the chamber sidewall at a time when critical longitudinal pressure gradients exist. A calculation performed using a strong, permeable bag (i.e., 0.6-MPa rupture strength), however, exhibited a tolerance to this delay in centercore functioning without the formation of large pressure waves, evidently a result of pressure equilibration via the persistent, circumferential ullage external to the bag.

In addition, an approximately 10-percent decrease in peak chamber pressure was observed for both strong-bag and full-diameter (i.e., quasi-one-dimensional) charge configurations. While differences in effective, macroscopic permeability may be responsible for this behavior, no single, consistent explanation has yet been formulated.

### III. CONCLUSIONS

We have demonstrated successful application of TDNOVA to the bagged-charge artillery problem. The treatment of radial flow in the vicinity of a centercore igniter, along with explicit recognition of flow of early combustion products external to the propellant package, is shown to impact significantly the predicted path of flame propagation and the resulting longitudinal structure of the pressure field, particularly in comparison to earlier one-dimensional simulations. Of major importance is the result that large differential pressures can accompany the maximum-charge-standoff configuration despite proper functioning of the centercore igniter.

We did not, however, reproduce the simple relationship between bag sidewall strength and pressure waves revealed in quasi-two-dimensional simulations reported previously<sup>6</sup>. The improved level of modeling afforded by TDNOVA paints an even more convincing picture of the complexity of the interplay between igniter, ullage, and packaging components. Interestingly, we even note a sensitivity of maximum chamber pressure to the degree of propellant confinement during flamespread.

We also observe, in agreement with earlier simulations, predicted ignition delays on the order of several milliseconds as opposed to the several tens of milliseconds experienced experimentally. Additional TDNOVA calculations performed with increased ignition temperatures for the black powder centercore and, indeed, with the centercore turned off entirely did not substantially increase ignition delays. Not unexpectedly, we find that a more complete picture of the sequence of events occurring during igniter functioning will be required to bring simulations of this portion of the cycle in accord with reality.

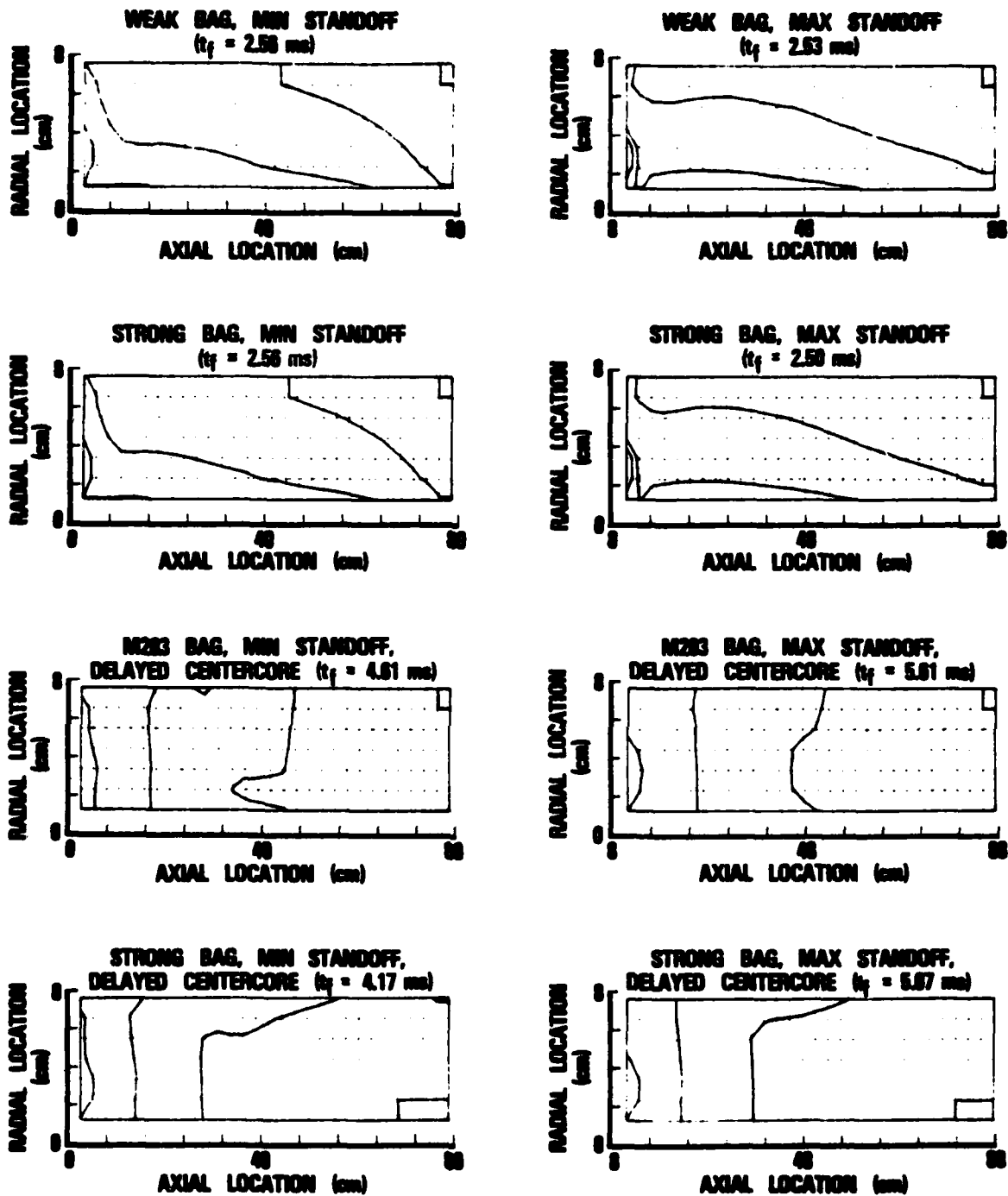


Figure 12. Predicted Flamespread Contours Using Altered Data Bases

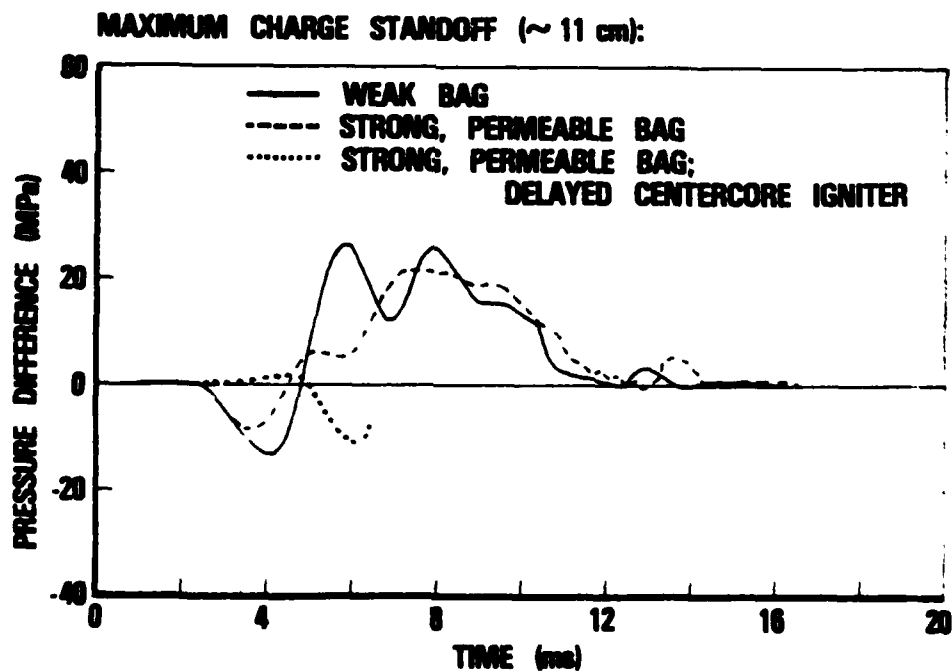
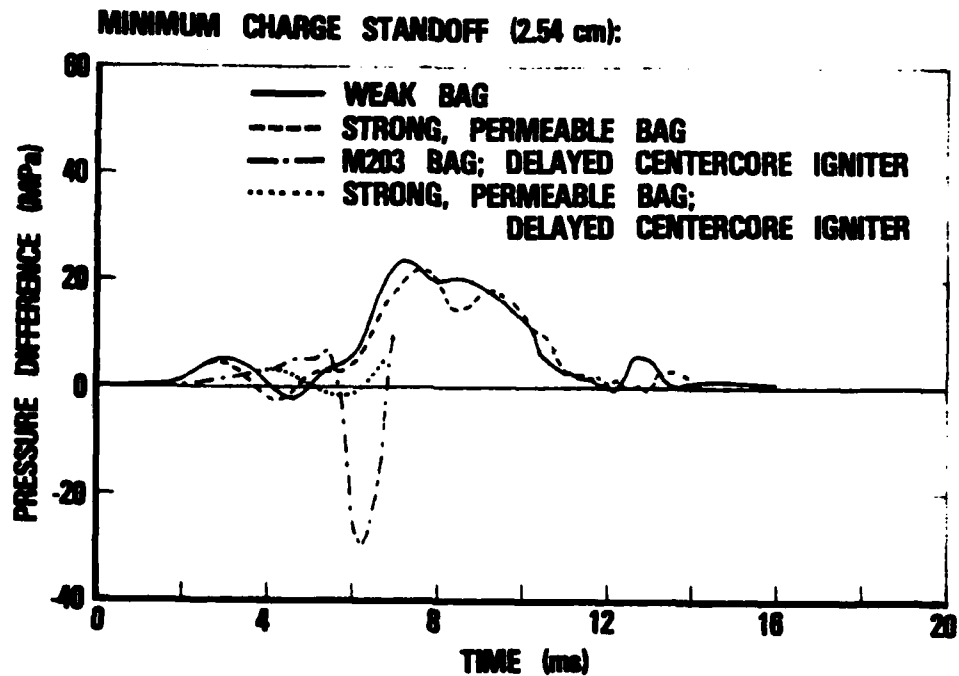


Figure 13. Predicted Pressure-Difference Profiles Using Altered Data Bases



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